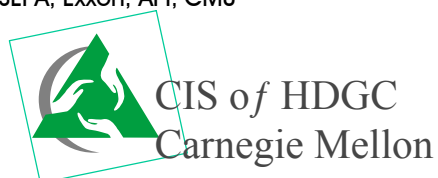


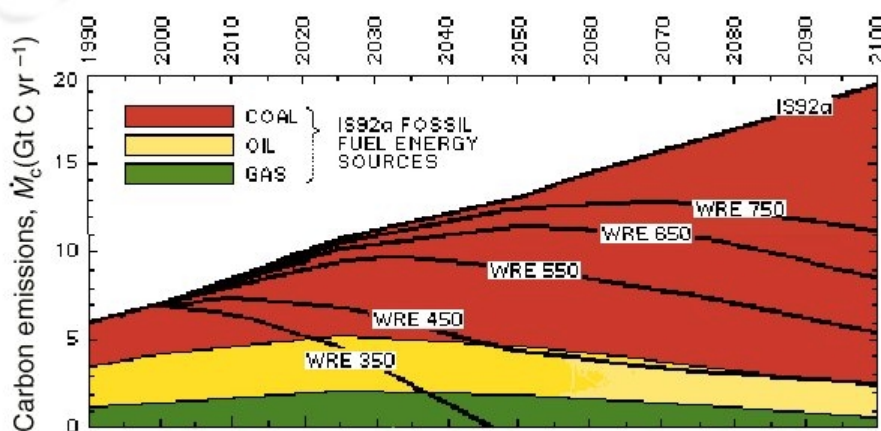
Fossil Fuels without Emission of CO₂: Implications for Climate Policy and Research Prioritization

David Keith
(keith@cmu.edu)
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Center for Integrated Study of the Human Dimensions of Global
Change
Carnegie Mellon University
National Science Foundation, USDOE, Electric Power Research
Institute, NOAA, USEPA, Exxon, API, CMU



How much do we need to cut CO₂ emissions?

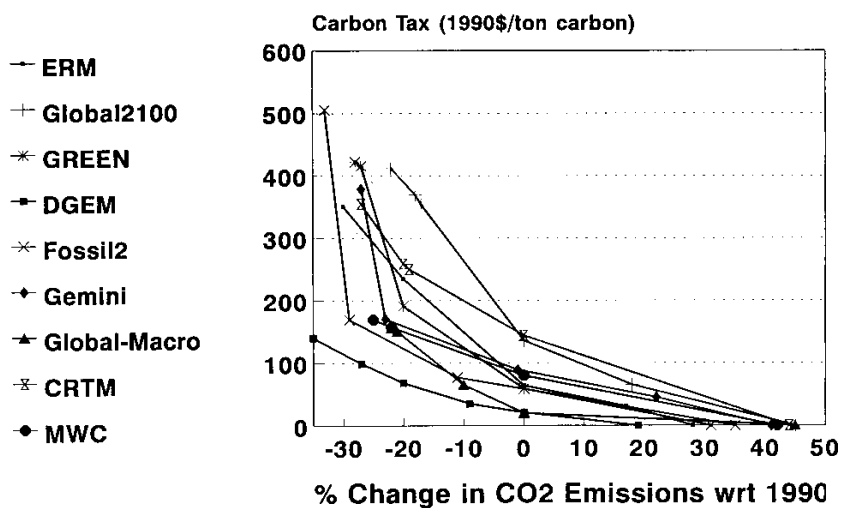


IS92a Emissions scenario

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How much will it cost?

Energy Modeling Form: Tax for emissions reductions
in 2020 relative to 1990 baseline.



Separating Energy from Carbon

Routes to separation

- Reform fuel to make hydrogen & CO₂.
- Burn hydrocarbon in air then capture CO₂ from combustion products.
- Separate oxygen from air then burn hydrocarbon in pure oxygen.

Core separation technologies

- Absorption in liquid solvents.
- Membrane gas separation.
- Adsorption on solid surfaces.
- Hydrate formation.
- Low-Temperature Distillation.
- Chemical looping.

Sequestration

Geological

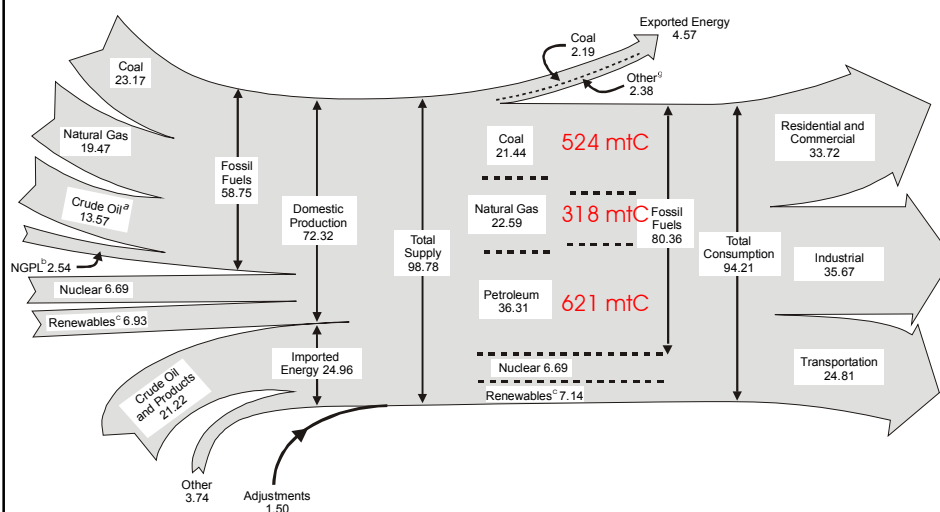
- Depleted oil and gas reservoirs: 200-500 GtC
- Deep saline aquifers: 10^2 - 10^4 GtC
- Deep coal beds: 100-200 GtC
- Chemical reaction with Silicate rocks.

Oceanic

- Capacity is large: $\sim 10^3$ - 10^4 GtC; depending on the "acceptable" degree of acidification.
- Atmosphere-ocean carbon equilibrium: $\sim 80\%$ in ~ 300 years.

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Carbon Management Potential: Fuel and sectorial end use



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Sequestration potential: Energy distribution networks

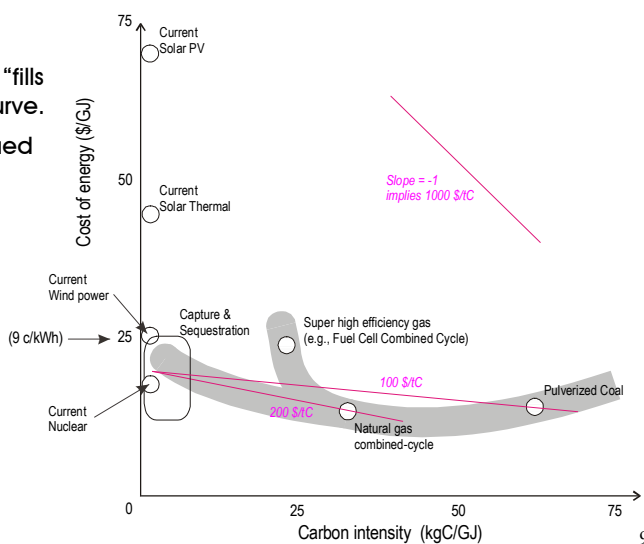
Networks offer potential for incremental entry of carbon management

- Electricity
 - Carbon-free energy distribution
 - Electricity generation most likely candidate for sequestration
 - Cost will probably be in the range 50-150 \$/tC.
- Natural gas
 - Comparatively low carbon primary energy carrier
 - Incremental decarbonization via CH_4 / H_2 mixtures?
 - Ease of conversion to H_2
 - Cost (equivalent tax) to make $\text{CH}_4 \rightarrow \text{H}_2 + \text{CO}_2$ competitive is about 100 to 180 \$/tC.

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Carbon management in the electric sector: Economics

- Sequestration “fills in” the cost curve.
- Costing plagued by baseline problems.



Why expect sequestration to play big role in electricity generation?

- Given existing technologies the cost of electricity with sequestration is expected to be less than or equal to current costs for renewables
- Reasons to expect the cost to fall
 - Multiple independent technological routes to separation and sequestration
 - Rapid increase in interest and private funding suggest possibility of rapid innovation
- Institutional advantages for sequestration vs non-fossil
 - A match for grid with respect to sizing and dispatch
 - Same suppliers of power conversion equipment, and fossil energy.
 - Fossil energy companies have expertise for geological sequestration.

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ICM in Transportation: Barriers and Opportunities

- Economies of scale in collection and sequestration means we must use a carbon free fuel: electricity or hydrogen
- Incremental entry difficult. Economies of scale and network effects work against introduction of new vehicle fuel.

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Carbon management in transportation

- Current focus is on fuel cell vehicles
 - Driver is air quality not climate: Particularly the California ZEV.
 - Vehicles would either use H₂ directly or would reform methanol or gasoline on-board.
 - DaimlerChrysler plans to spend 1.4 \$bn over the next half decade.
 - Several companies have announced plans to bring fuel cell cars to market in the next 5-10 years.
- Barriers to H₂ powered vehicles
 - High power plant cost and mass
 - Dynamic range problem → low acceleration
 - Low density of H₂ storage
 - → insufficient range
 - economies of scale and network effects pose significant barriers to incremental entry of this technology.

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Nothing can go wrong...

- Slow re-release of sequestered carbon
 - Energy penalty of ICM ⇒ more CO₂ per unit final energy ⇒ thus sequestration into leaky reservoirs could *increase* future atmospheric CO₂ concentrations.
- Novel environmental risks
 - Catastrophic venting
 - Increase in ocean acidity
- Increased reliance on fossil fuels
 - What if supplies are smaller than we now believe?
- Institutional factors may drive rush to adopt sequestration over other options

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Research Prioritization

Metrics for prioritization

- Analysis of the easiest places for CM to enter the energy system: Incremental entry is a key
- Likelihood of technical payoff
- Marginal impact of new research funding relative to existing funding
- Likely public acceptability and scale of ultimate implementation

Examples

- Oceanic vs geological sequestration
- Pre-combustion separation (H₂ production) vs post combustion

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Implications

- Supply curve for emissions mitigation rises less steeply than we thought
- Carbon taxes look even better as a regulatory mechanism.
- Fundamental change in thinking about the future of fossil fuels.
- Potential make the fossil fuel industry the engine of abatement rather than the break
- Wedge issue for the environmental community

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